Opportunities for Ultrafast X-ray Physics

New science at the APS with short x-ray pulses

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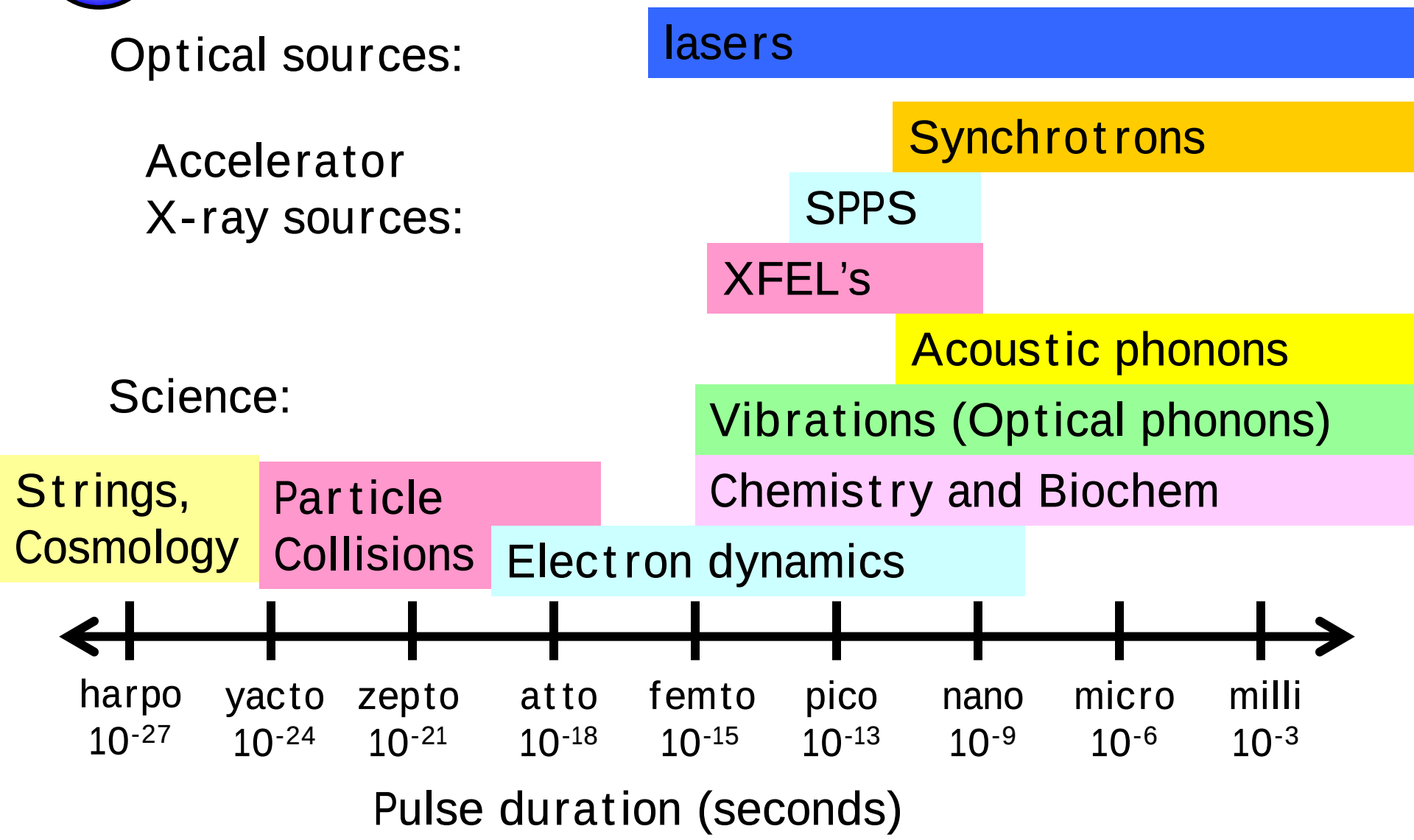
FOCUS Center, University of Michigan
APS Workshop on Time-Domain X-ray Science
Lake Geneva, WI, August 2004

Ultrafast X-ray Science

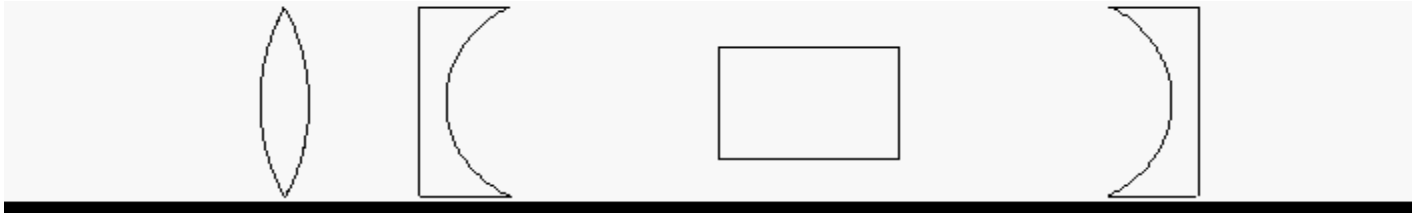
- What's Ultrafast?
- X-ray Science Contributions to Ultrafast Science: 1fs to 1ns
- Challenges and Opportunities: Shorten the x-ray pulses at APS to ~1psec
- Ultrafast Science at SPPS

Ultrafast Sources and Science:

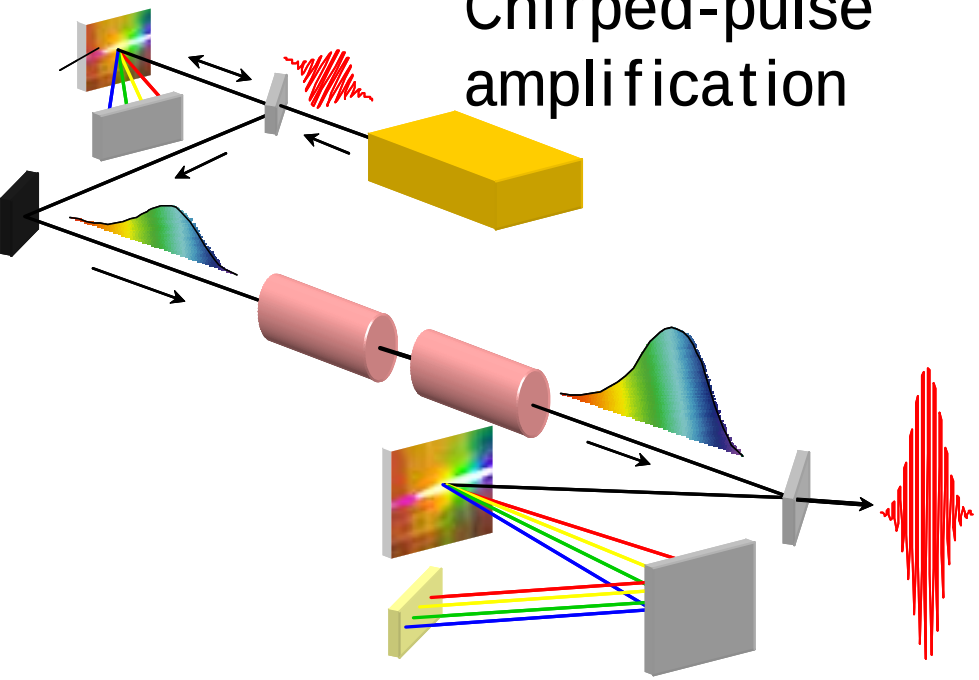


How did lasers get so ultra-fast?

Kerr-lens modelocking

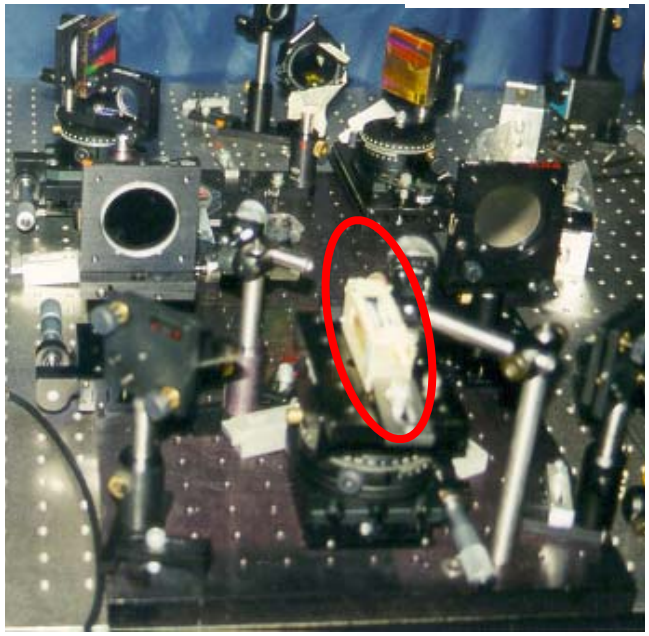


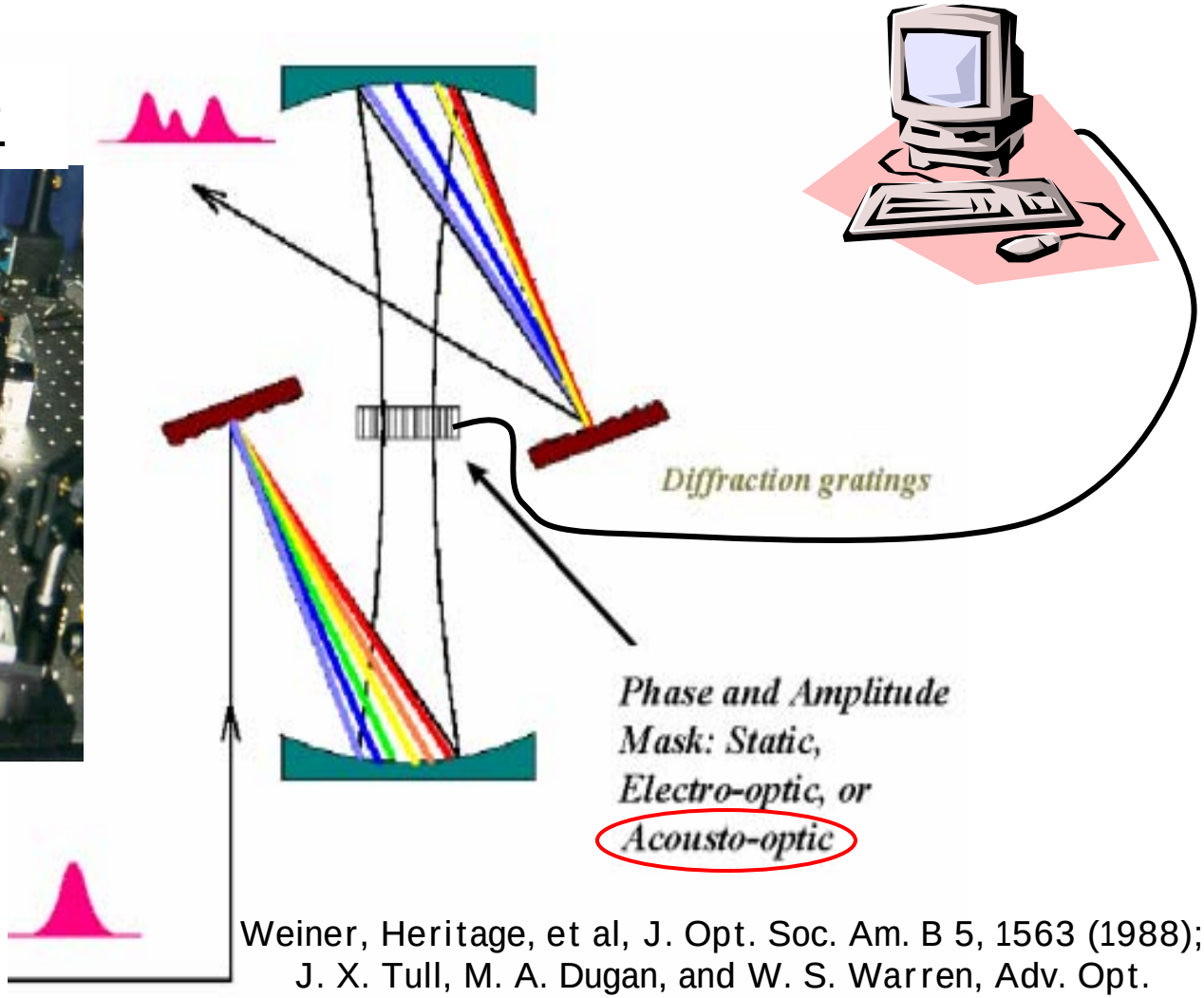
Chirped-pulse amplification



Optical Pulse Shaping

AOM Pulse Shaper

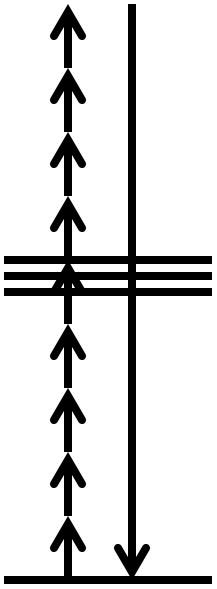


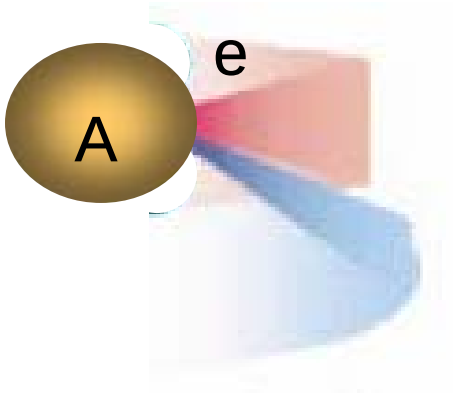


Weiner, Heritage, et al, J. Opt. Soc. Am. B 5, 1563 (1988); J. X. Tull, M. A. Dugan, and W. S. Warren, Adv. Opt. Mag. Resonance **20**, 1 (1997).

High Harmonics: Bremmstrahlung from atomic electrons driven coherently by the oscillating laser field

$E_{max}=3.17U_P$

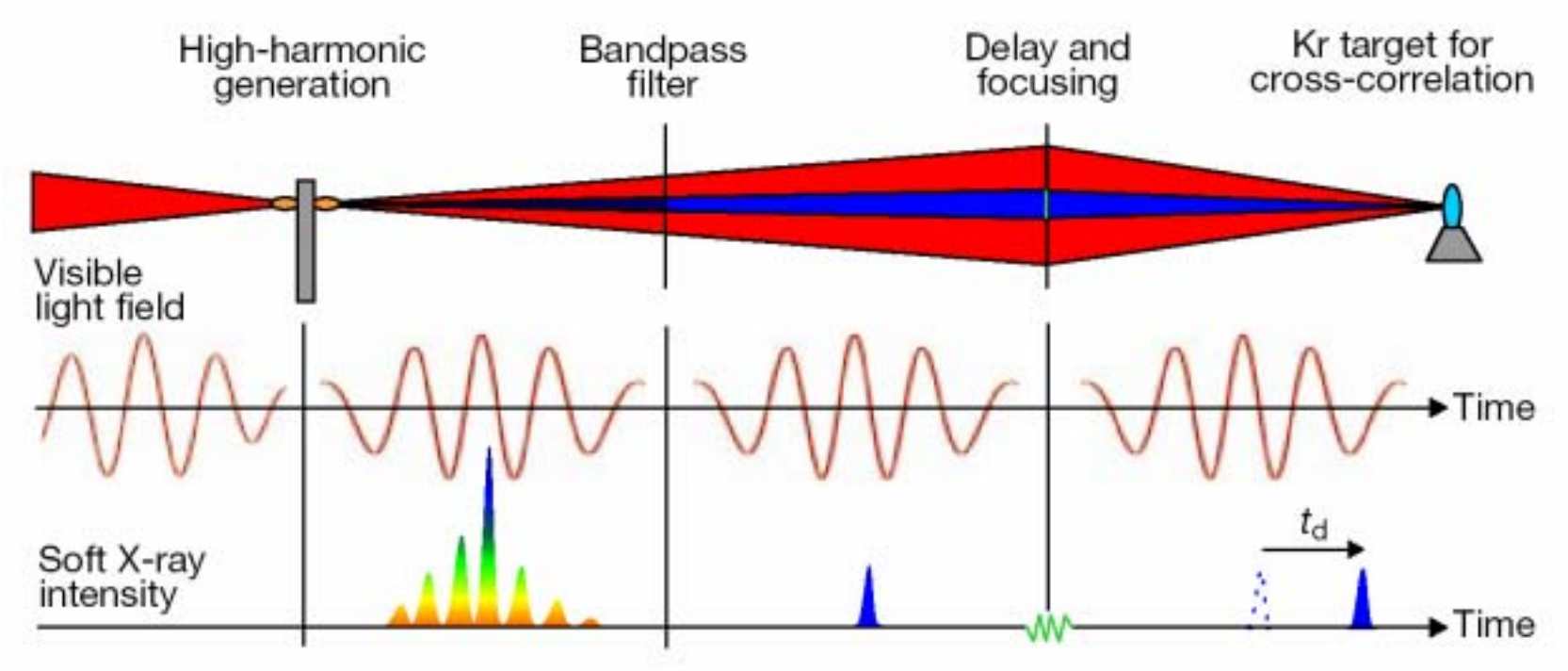




U_P=wiggle energy

High harmonics are fast (<1fs!) but soft (<0.5keV)

Sub-femtosecond pulses



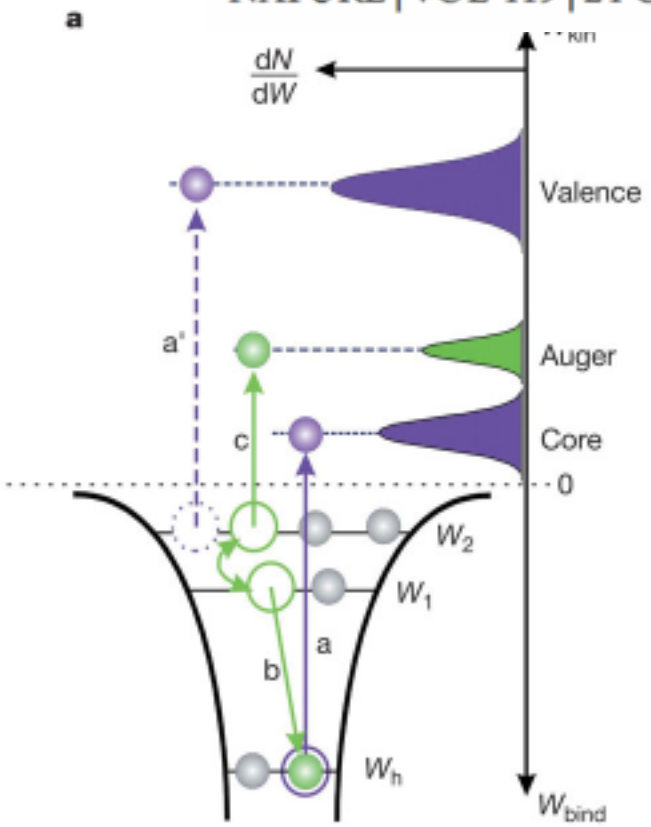
M. Hentschel, Nature **414**, 509 (01)

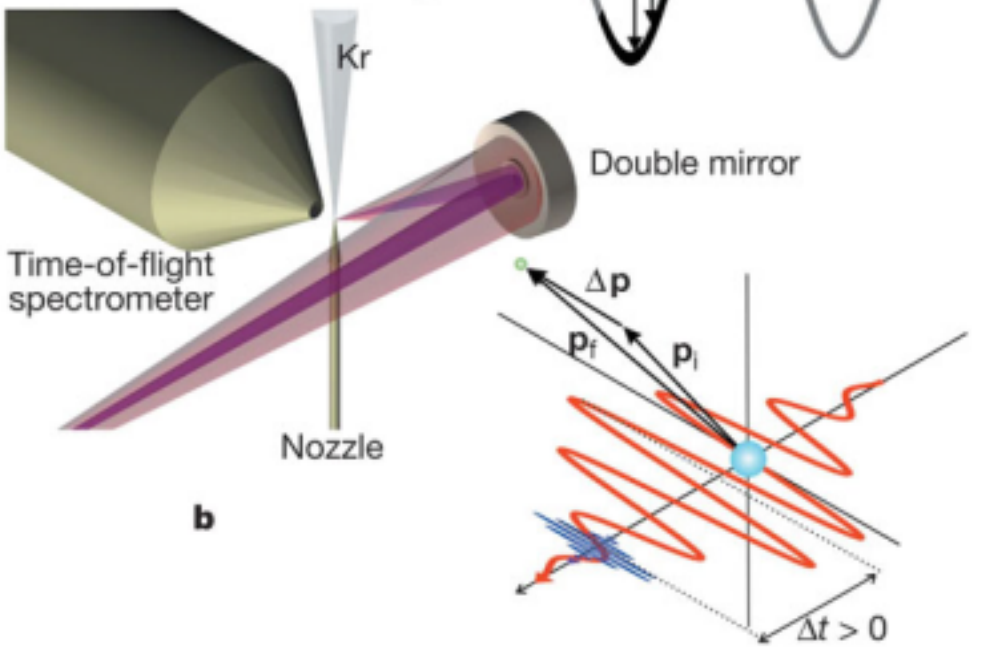
Attosecond high harmonics:

Time-resolved atomic inner-shell spectroscopy

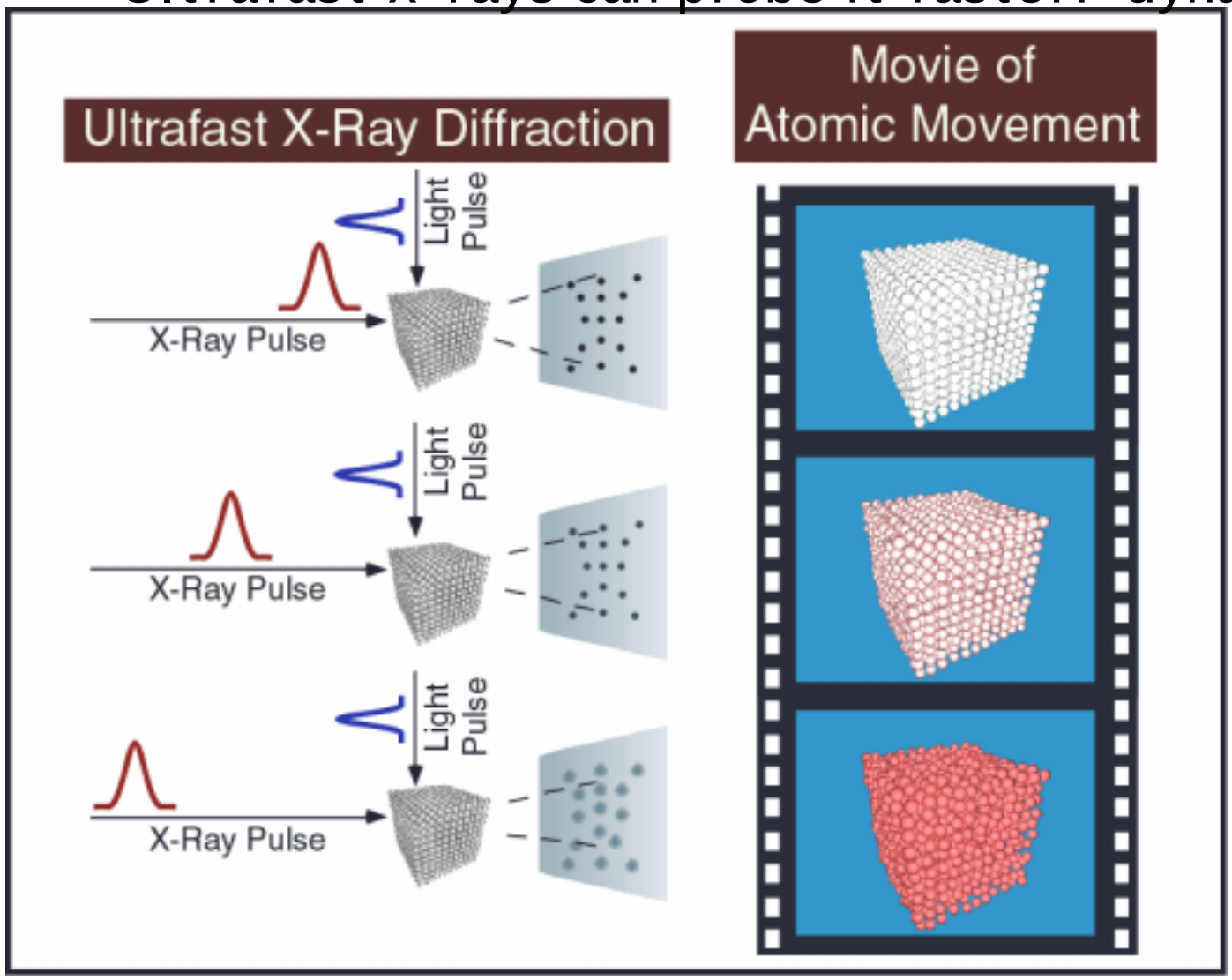
M. Drescher*†, M. Hentschel*, R. Kienberger*, M. Uiberacker*, V. Yakovlev*, A. Scrinzi*, Th. Westerwalbesloh†, U. Kleineberg†, U. Heinzmann† & F. Krausz*

NATURE | VOL 419 | 24 OCTOBER 2002 |





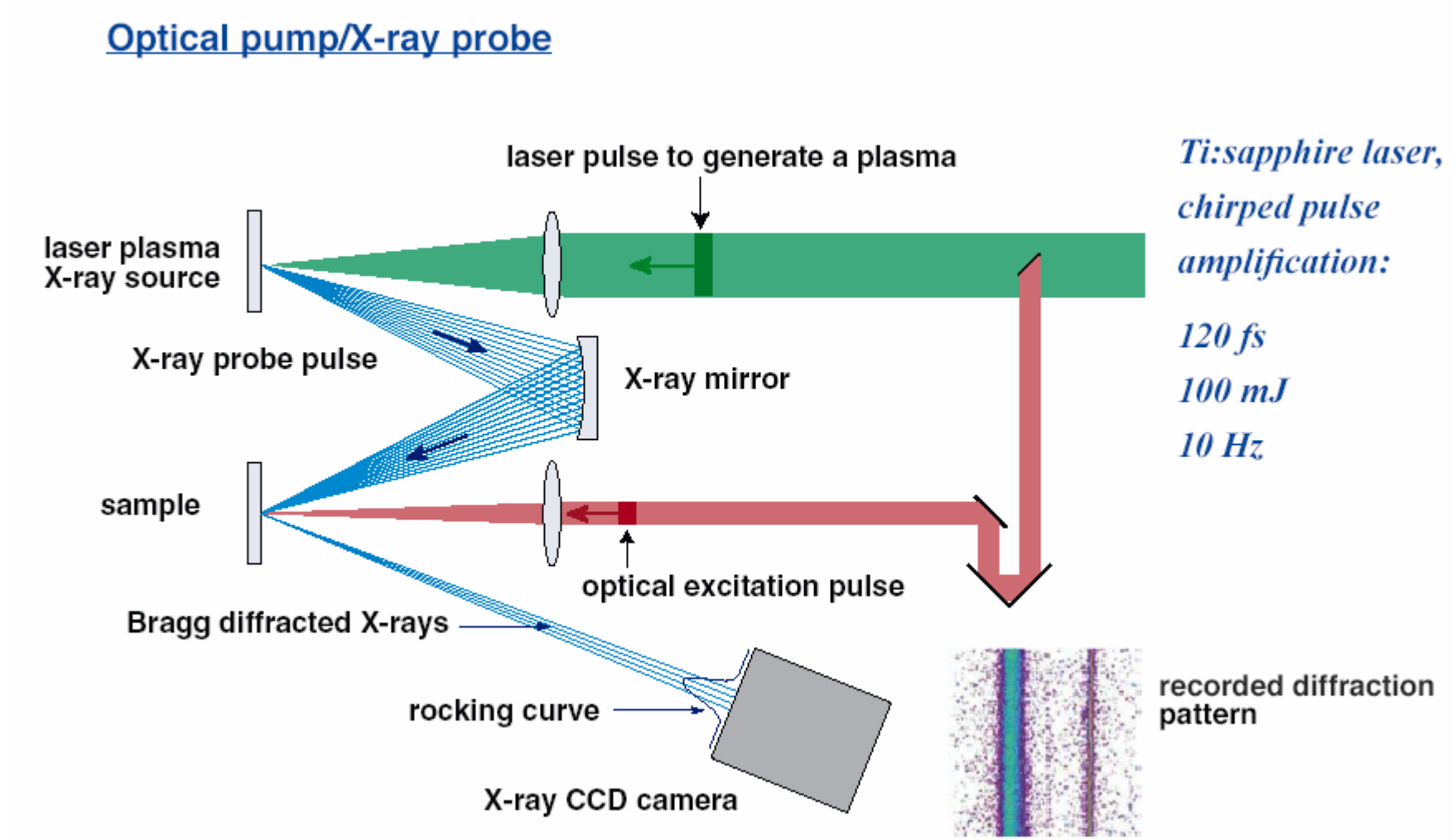
Hard X-rays can probe structure
Ultrafast x-rays can probe it faster: dynamics



Stuff moves in 0.01-10 ps

Source: LCLS – The First Experiments; graphic from C. Siders

Laser-based x-ray experiments use pump-probe technique



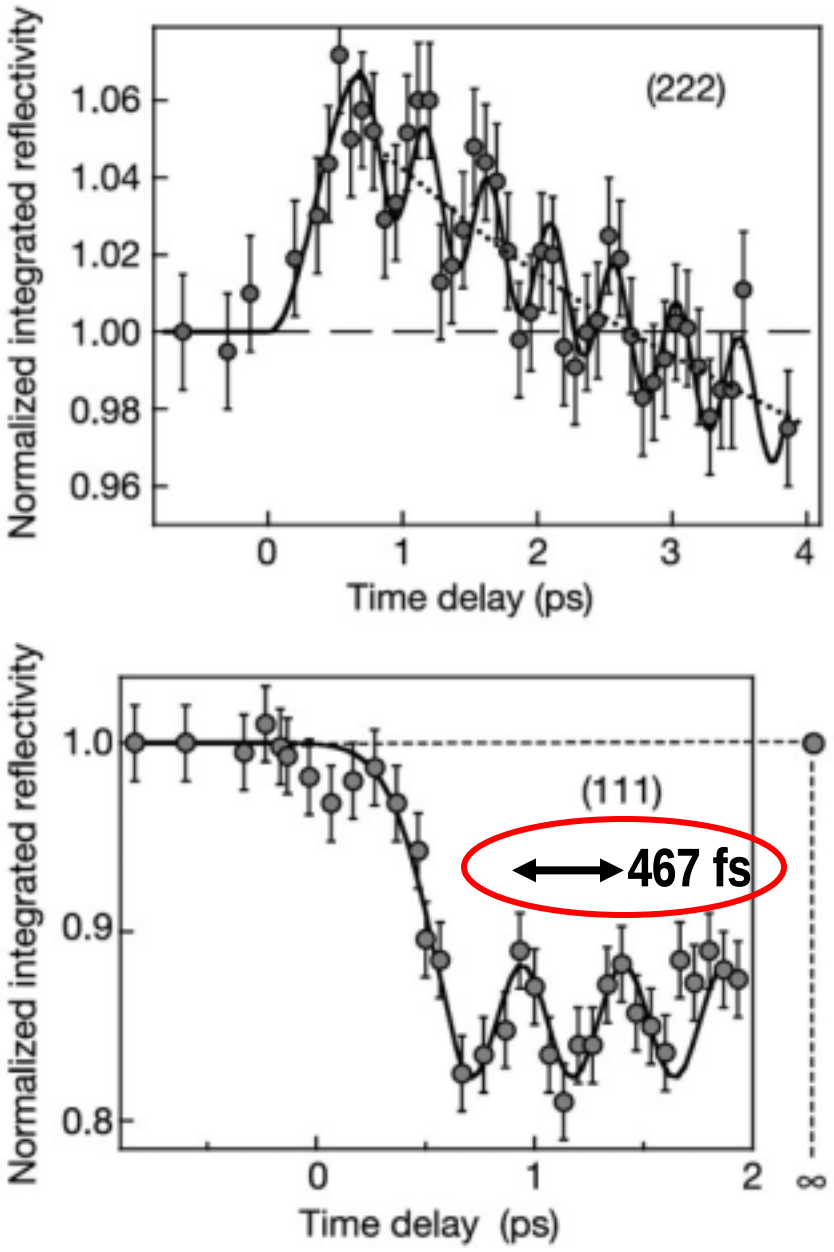
D. von der Linde, Universität Essen, Institut für Laser- und Plasmaphysik

Laser plasma x-rays:
Time resolution < 1ps,
but not many photons

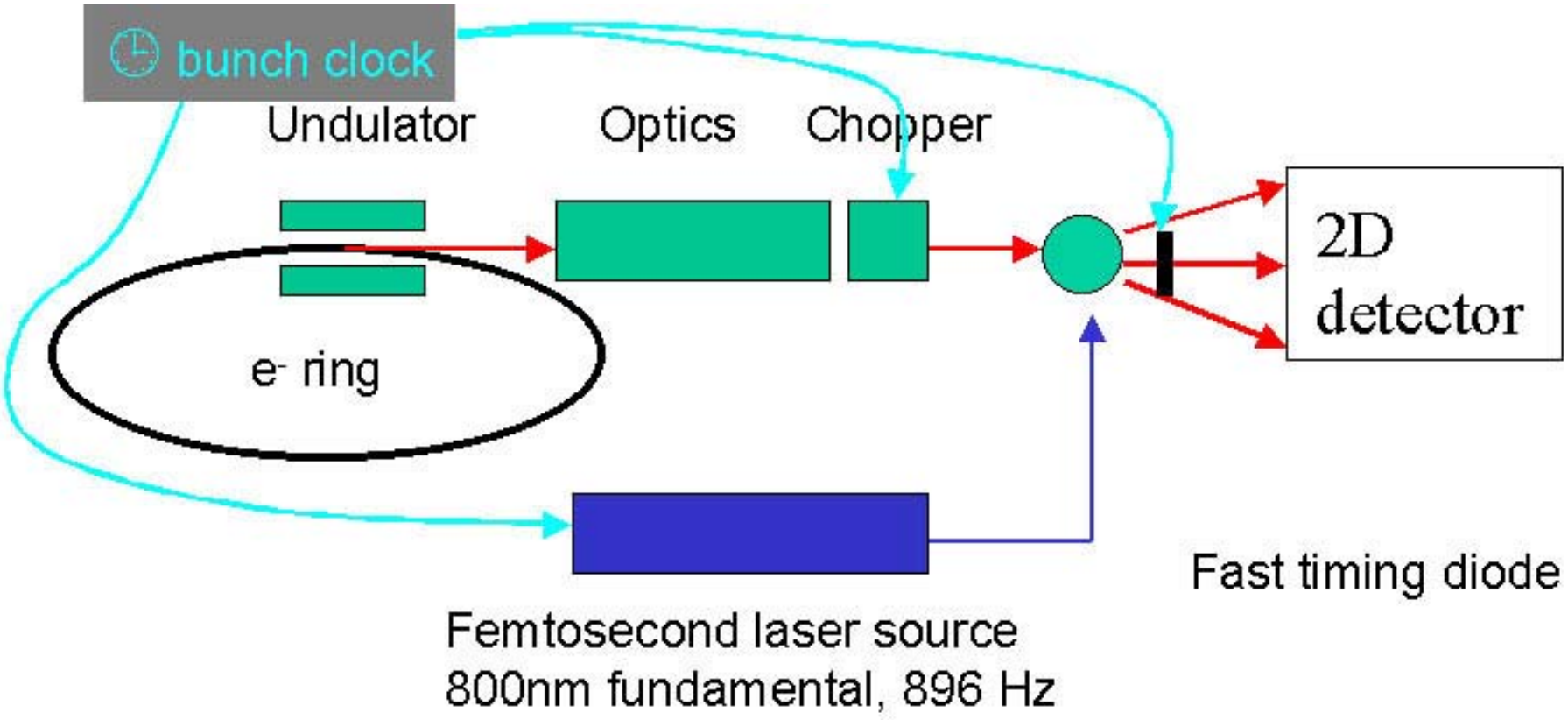
Femtosecond X-ray measurement of coherent lattice vibrations near the Lindemann stability limit

Klaus Sokolowski-Tinten*, Christian Blome*, Juris Blums*, Andrea Cavalleri†, Clemens Dietrich*, Alexander Tarasevitch*, Ingo Uschmann‡, Eckhard Förster‡, Martin Kammler§ Michael Horn-von-Hoegen* & Dietrich von der Linde*

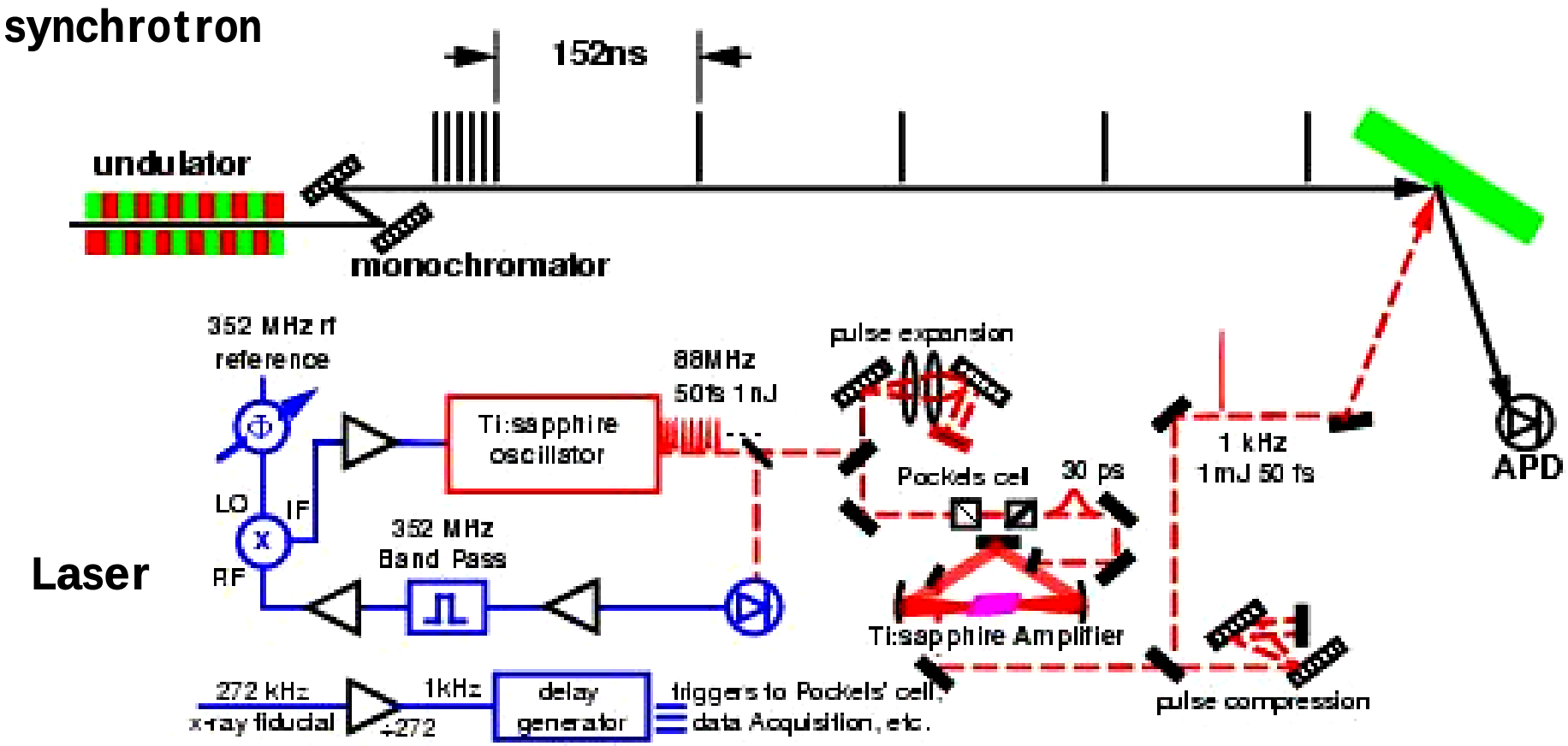
Nature, **422**,p. 287 (2003)



APS: Lots of photons; not much time resolution (100 ps)



Synchronizing the x-rays and the laser to <10 ps:



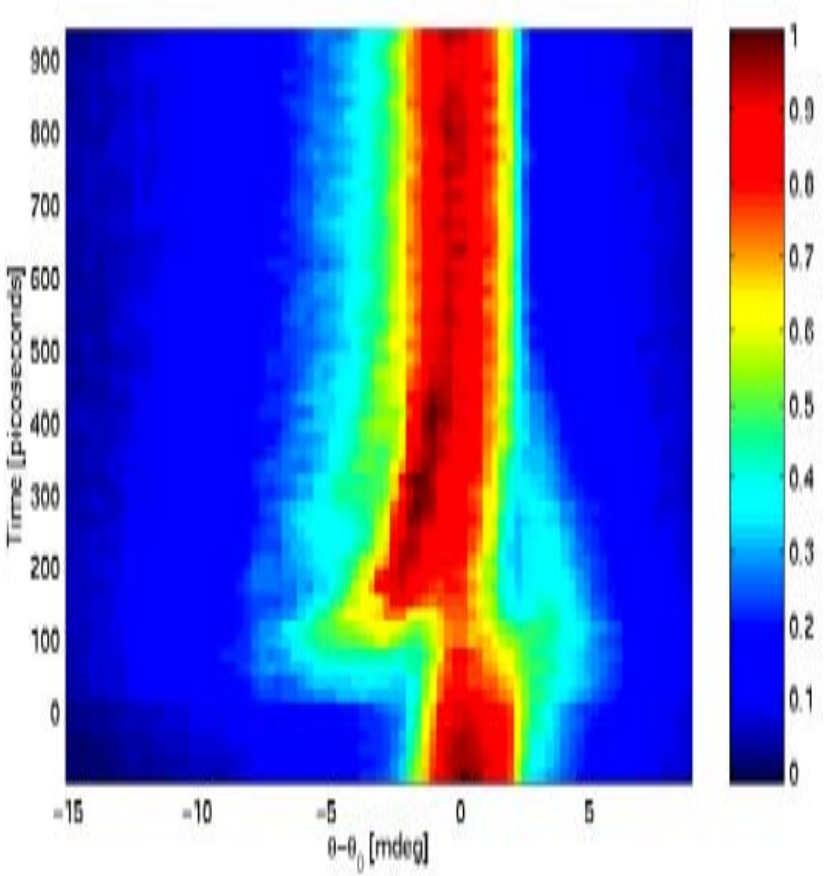
Time-resolved Bragg Diffraction: Coherent Acoustic Phonons

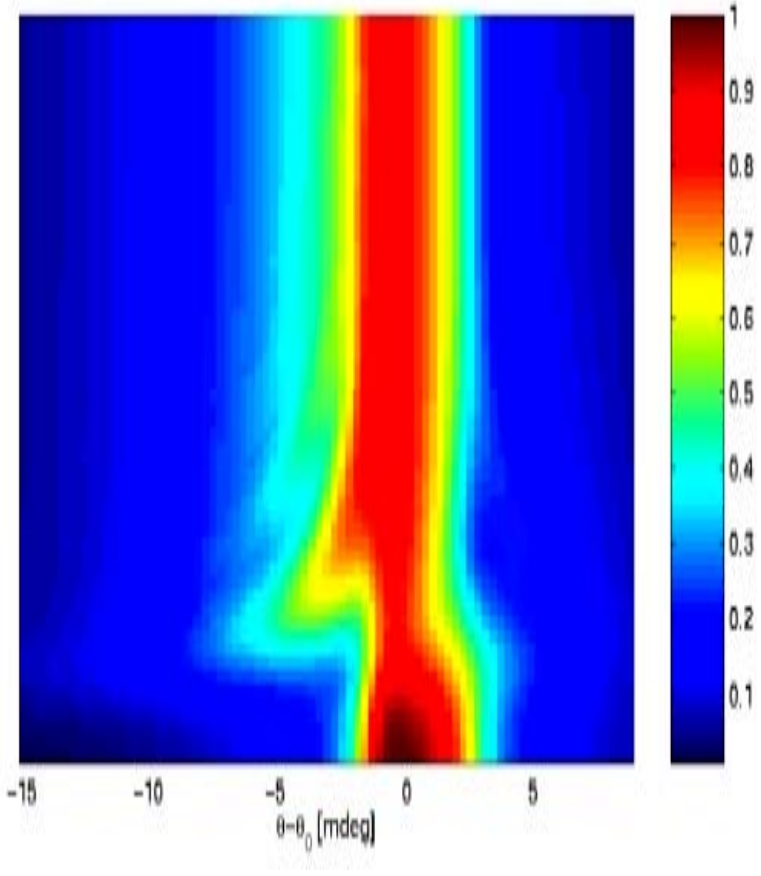
Laser Pump/X-ray Probe

Reis *et al.* Phys Rev. Lett.(86) 2001

Impulsive Strain Generation

(Thomsen *et al.* Phys Rev. B (24) 1986.)

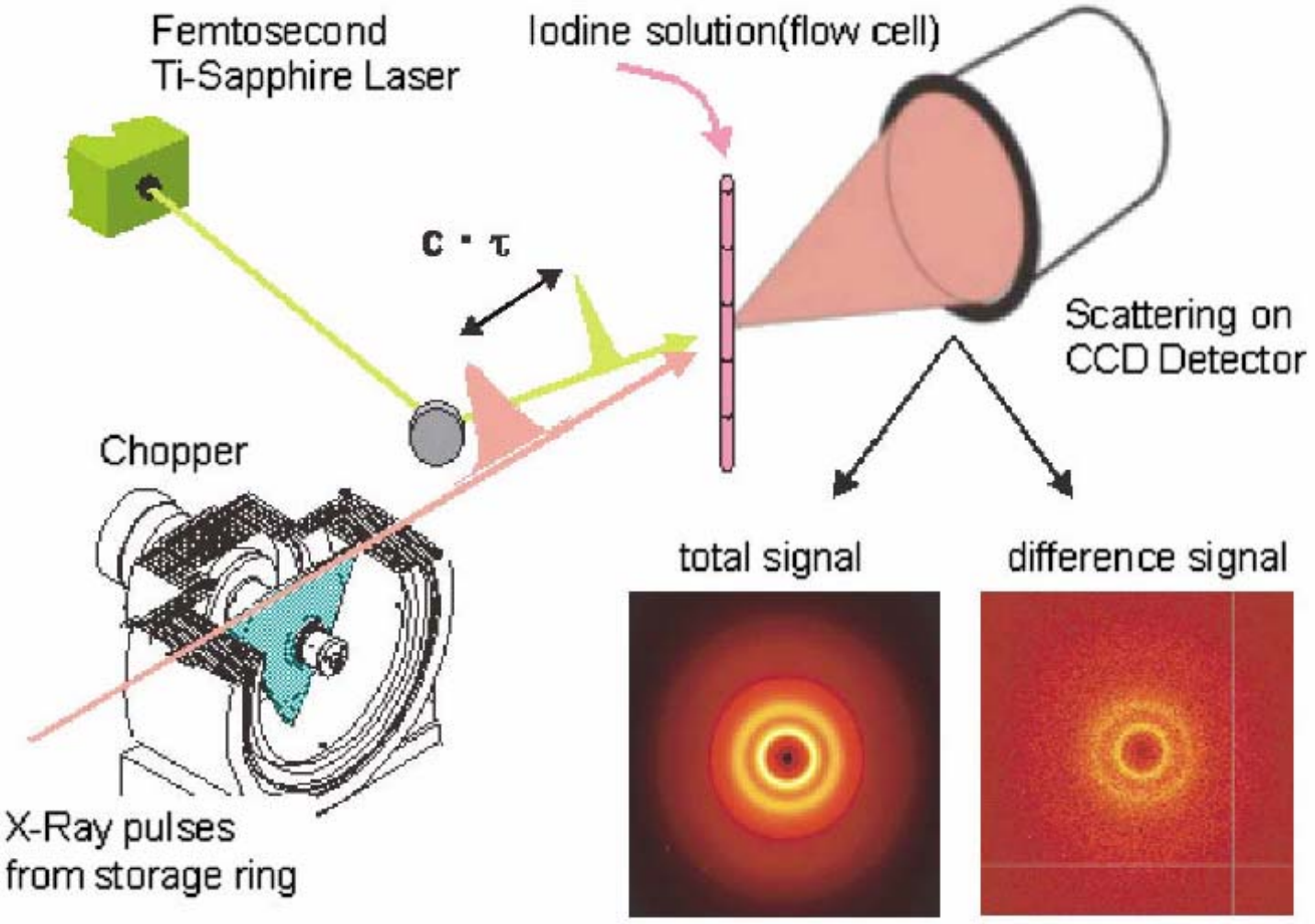




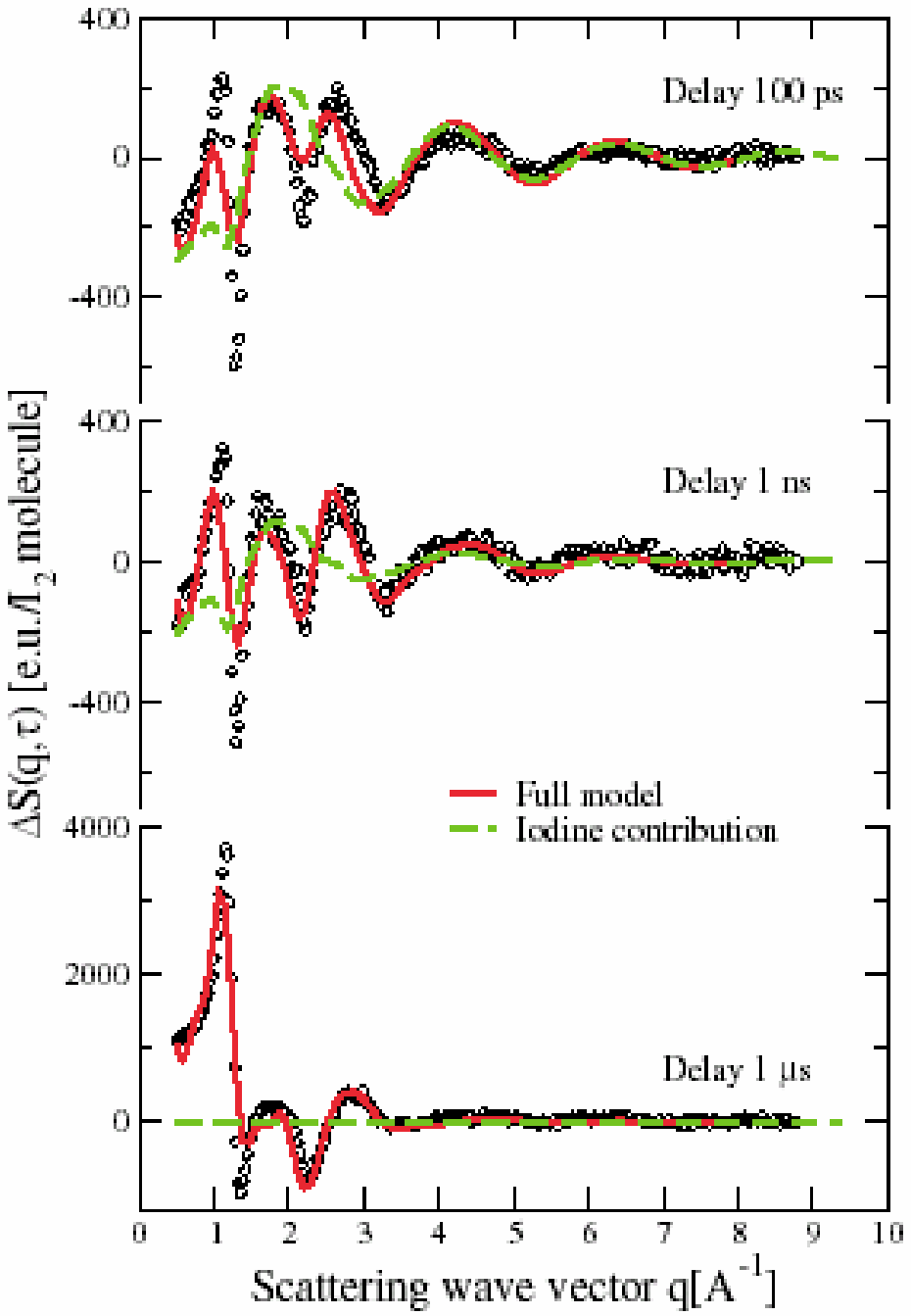
experiment: InSb 111, 10mJ/cm^2

simulation: 100ps & 1.25mdeg conv.

Picosecond time-resolved x-ray diffraction can be used to monitor atomic motions in liquids



Plech et al. Phys. Rev. Lett. **92**, 125505 (2004)

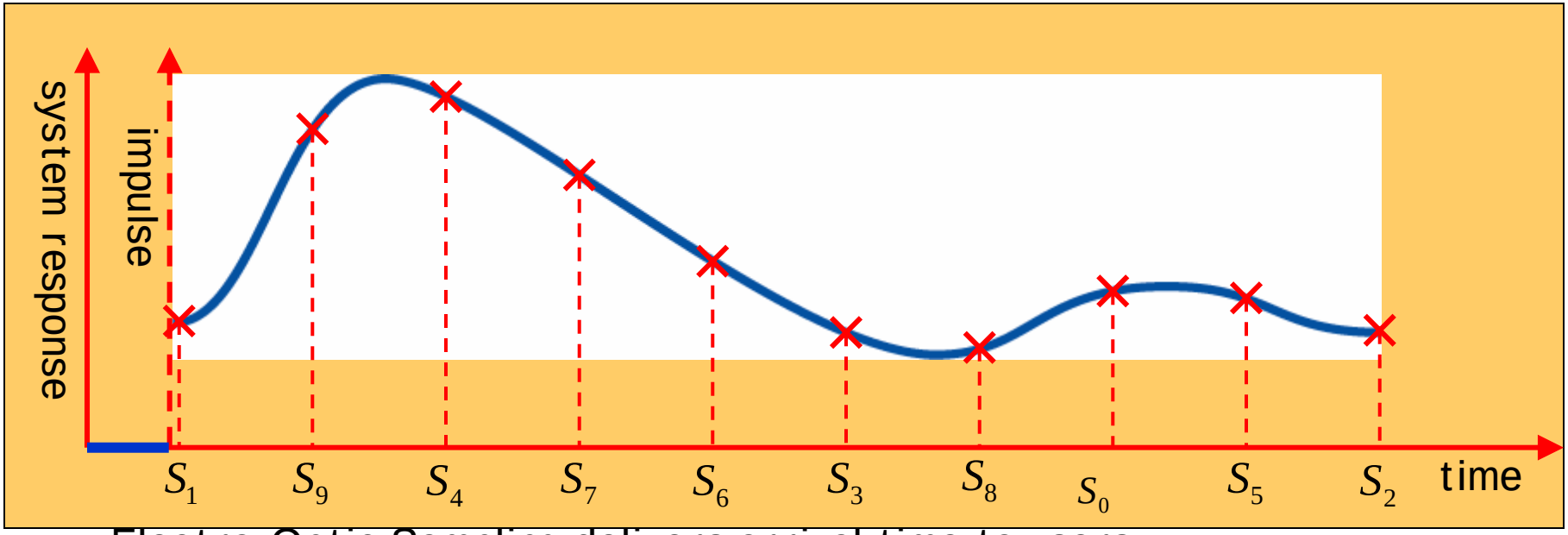


The motion of the molecule and solvent develop in less than 100 psec; we need better time resolution:

-Better synchronization
-Shorter x-ray pulses

Synchronization: Use sampling method:

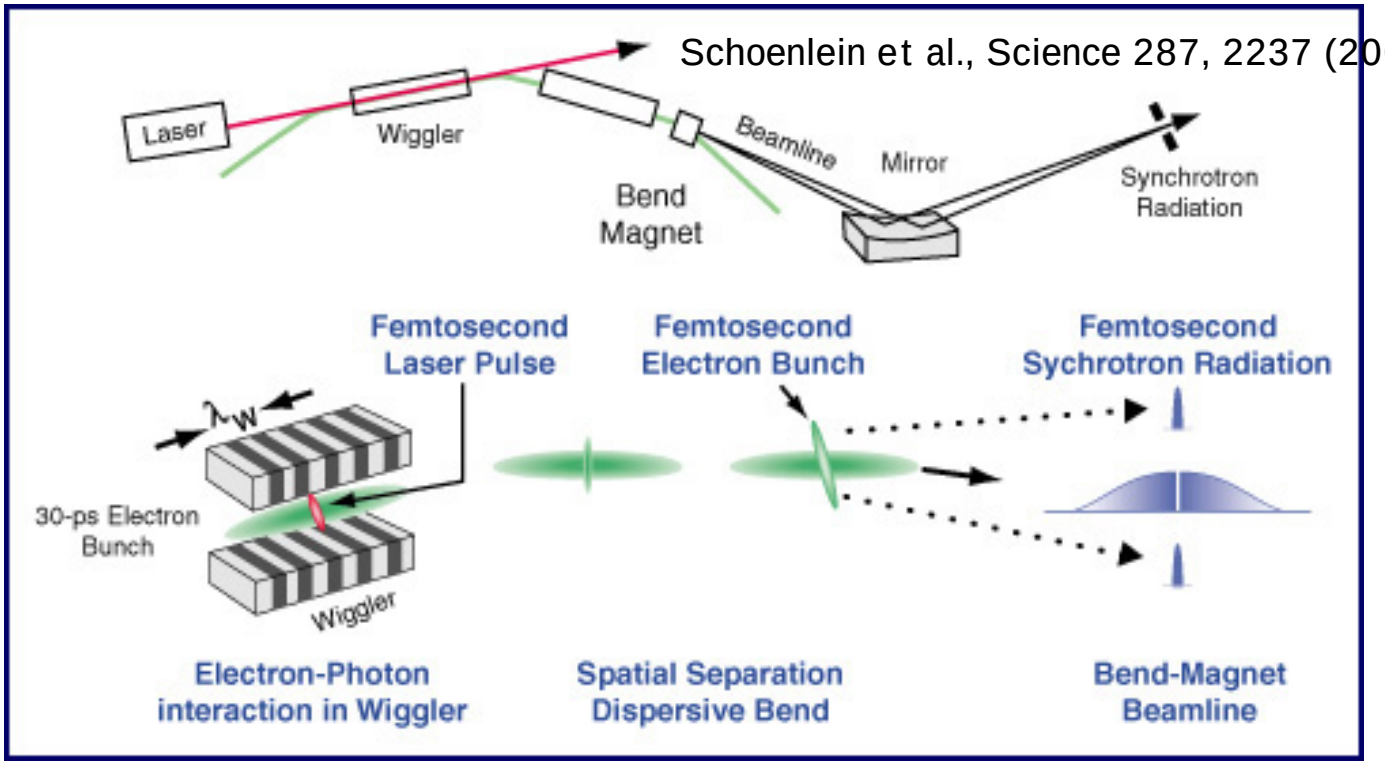
Typical time resolved experiment utilizes intrinsic synchronization between pump excitation and probe

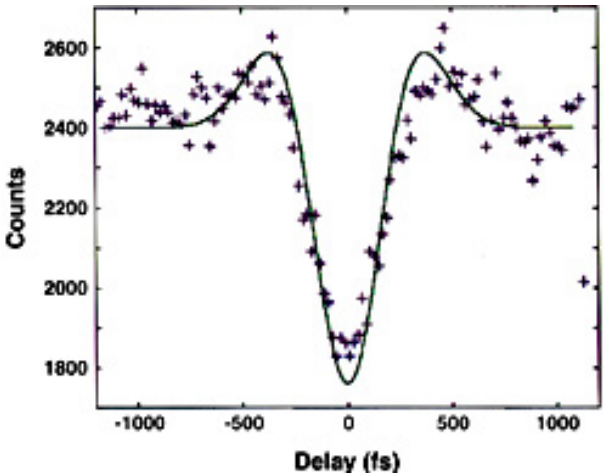


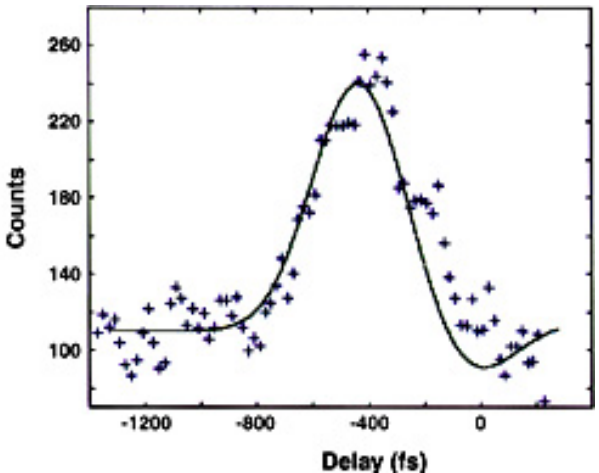
- Electro-Optic Sampling delivers arrival time to users
  - Pump-Probe experiments now possible
  - Machine jitter exploited to sample time-dependent phenomena

Shorter x-ray pulses at 3d generation synchrotrons

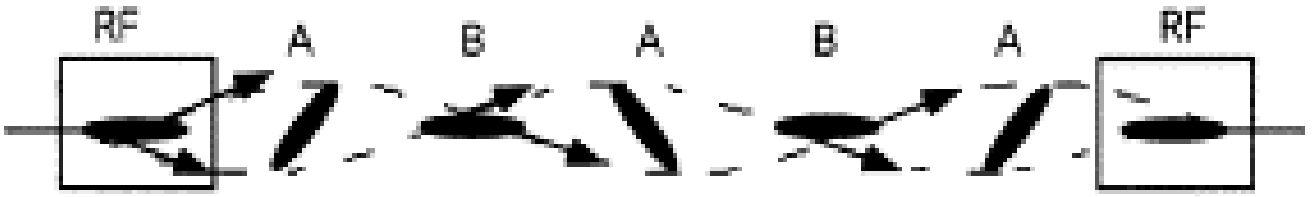
Schoenlein et al., Science 287, 2237 (2000).



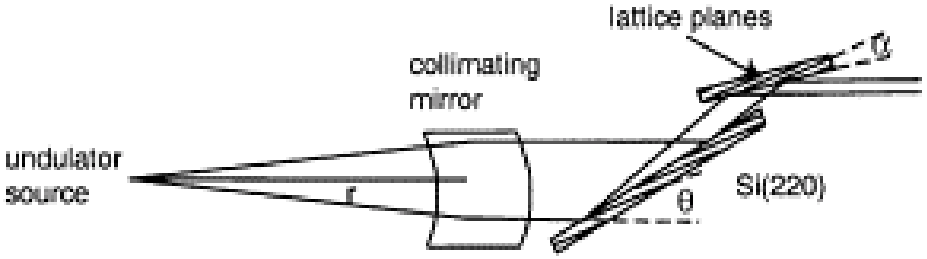




Shorter pulses are also possible at the APS (Zholents et al.)



A schematic of the beam coupling produced by the RF cavities operated at *E*110 mode.



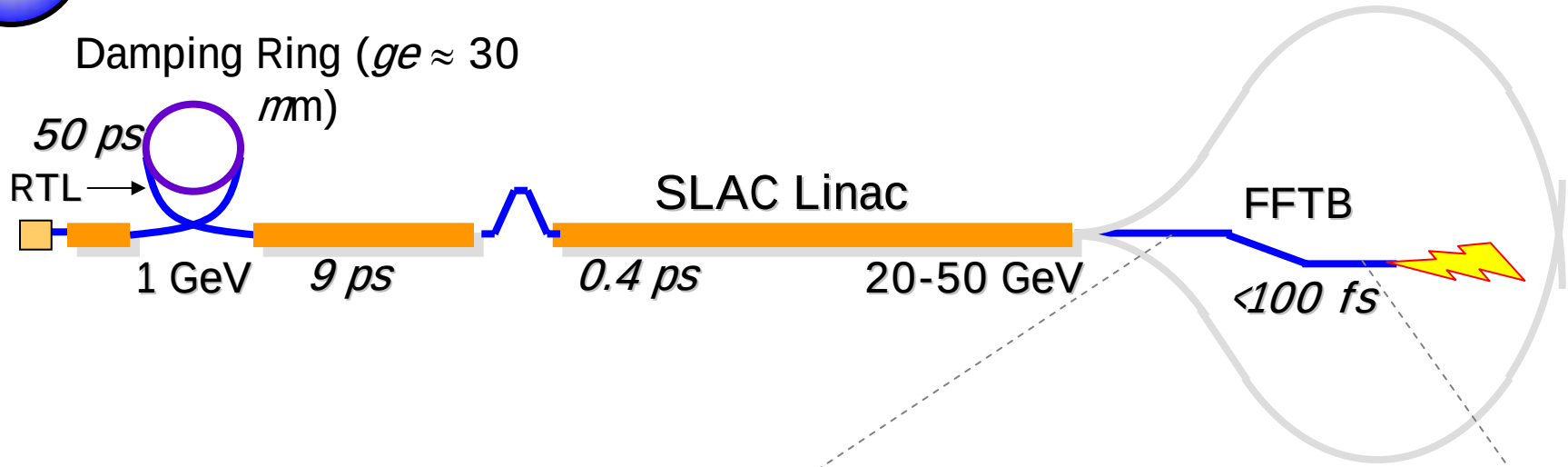
Optical scheme for pulse compression with a collimating mirror and a double asymmetrically cut crystal monochromator.

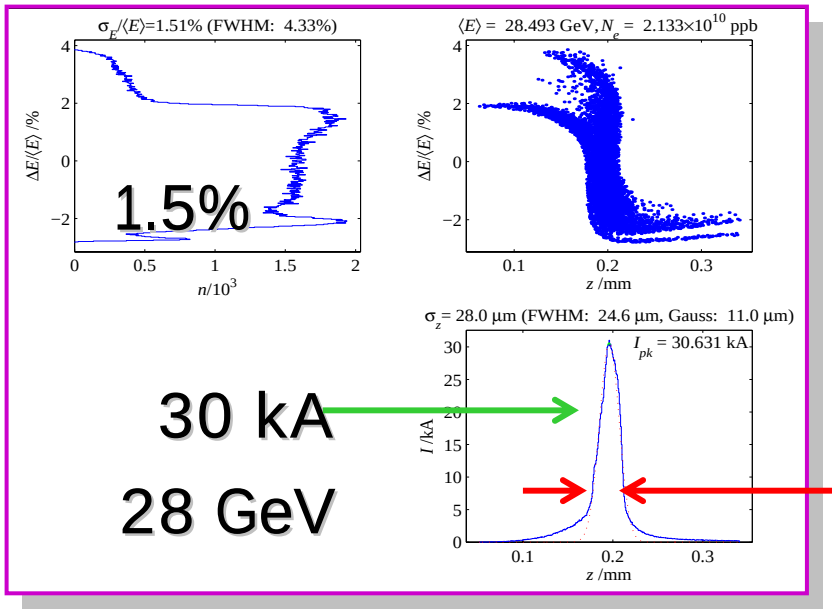
Zholents A, et al. NIM **425** (1-2): 385-389 APR 1 1999

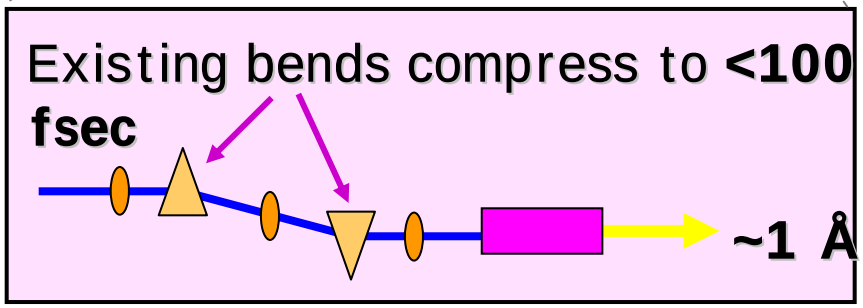
The Sub-Picosecond Pulsed Source (SPPS)

FOCUS

Short Bunch Generation in the SLAC Linac







80 fsec FWHM

SPPS Collaboration

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Aaron Lindenberg
Donnacha Lowney
Andrew MacPhee

APS Argonne Nat'l Lab

Dennis Mills

MSD Argonne National Lab

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Gosta Huldt

DESY

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Copenhagen University

Jens Als-Nielsen

Lund University

Jörgen Larsson
Ola Synnergren
Tue Hansen

Chalmers University of Technology

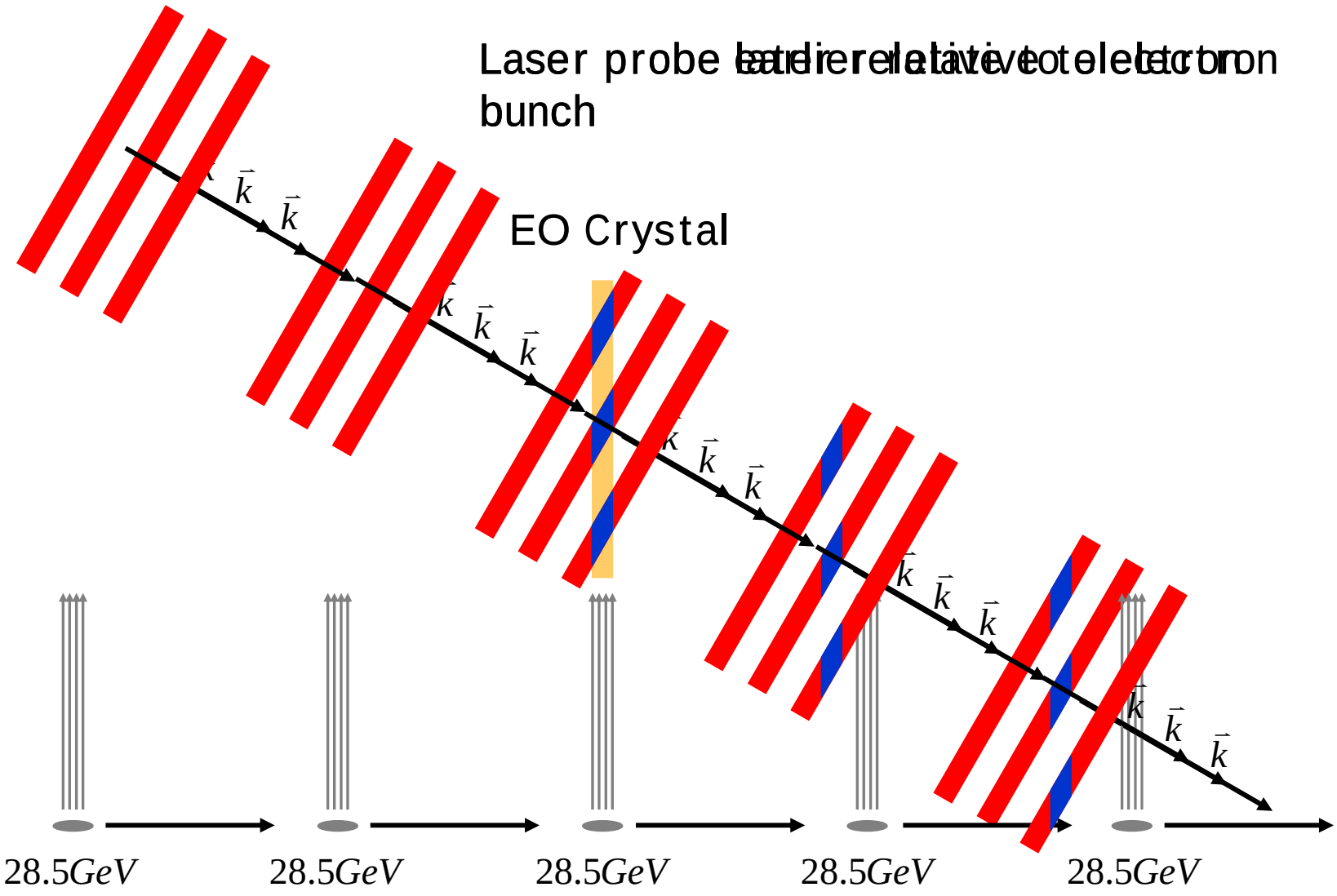
Richard Neutze

FOCUS

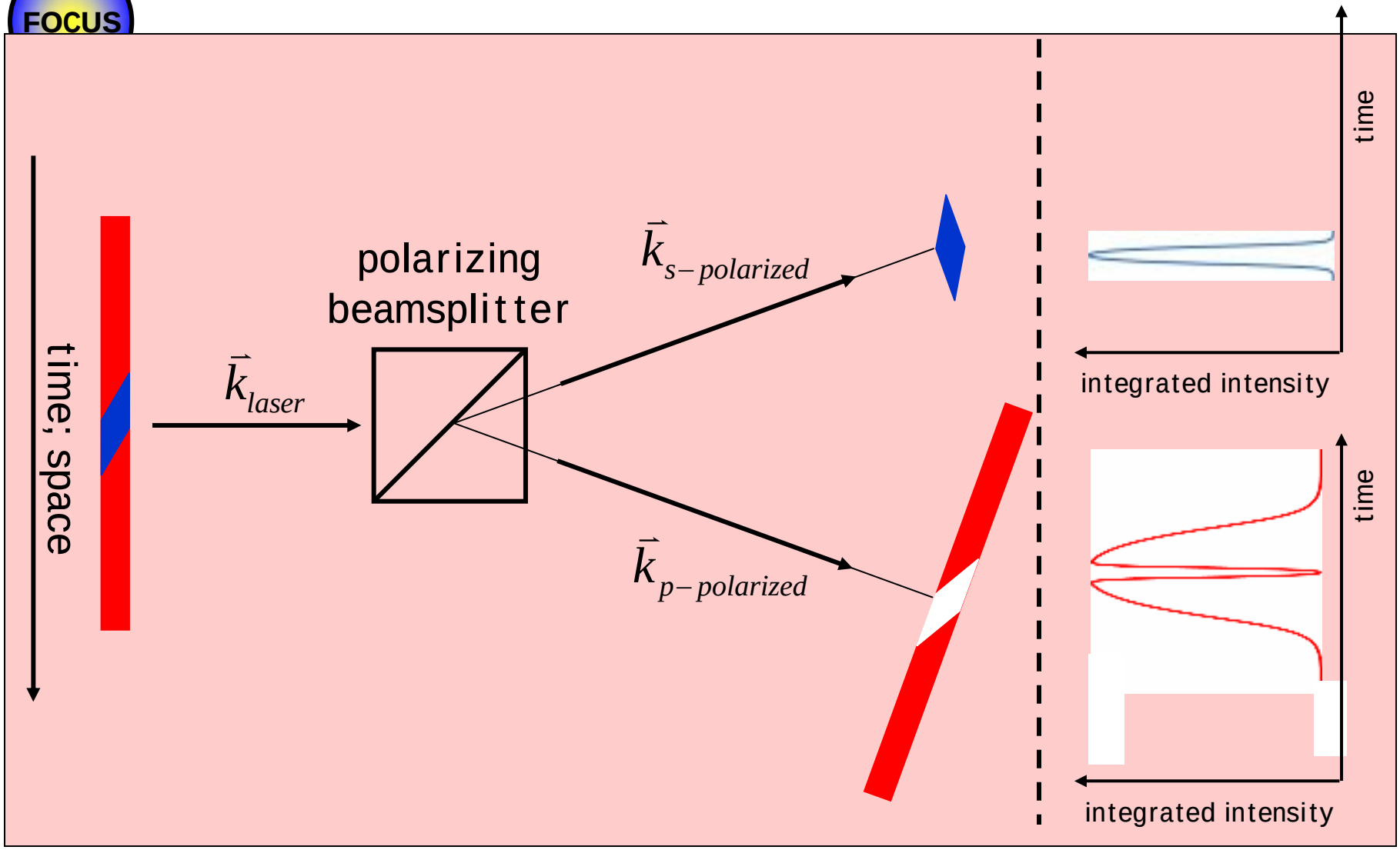
SPPS Facility


Undulator,
View upstream
Dave Fritz, Soo Lee, David Reis

Spatially Resolved Electro-Optic Sampling (EOS)



Spatially Resolved EOS



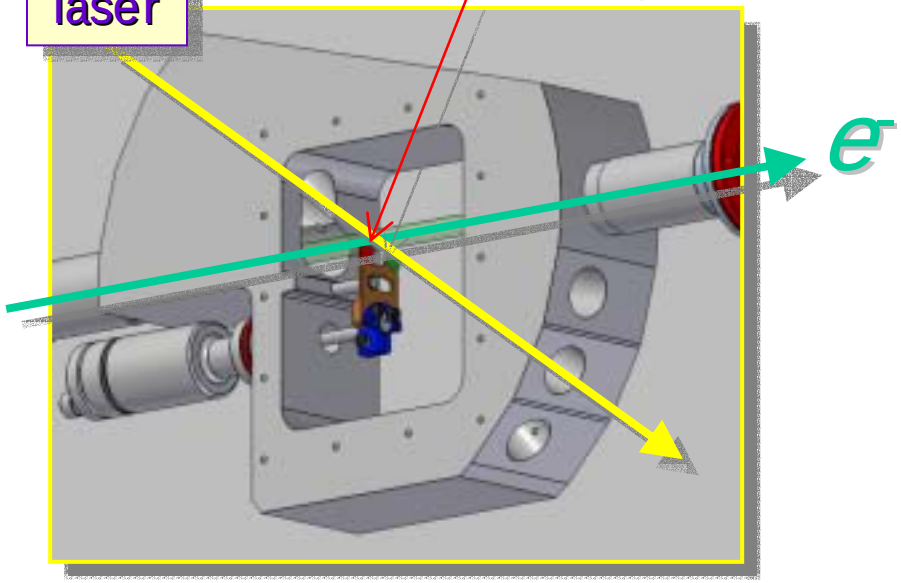
Arrival time and duration of bunch is encoded on profile of laser beam

Electro-Optical Sampling

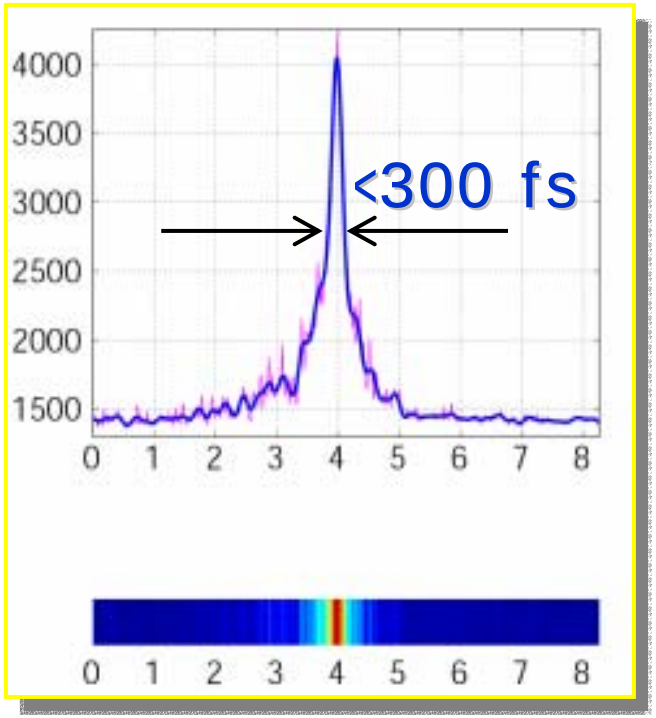
FOCUS

Ti:s laser

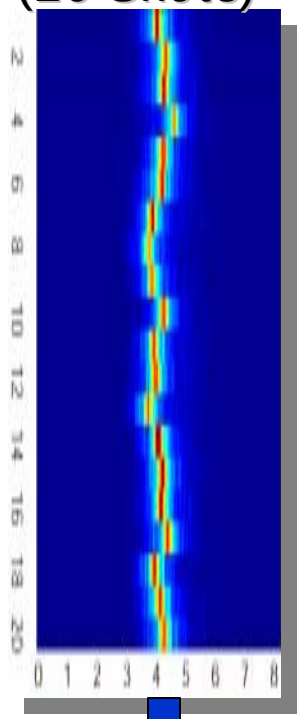
200 mm ZnTe crystal



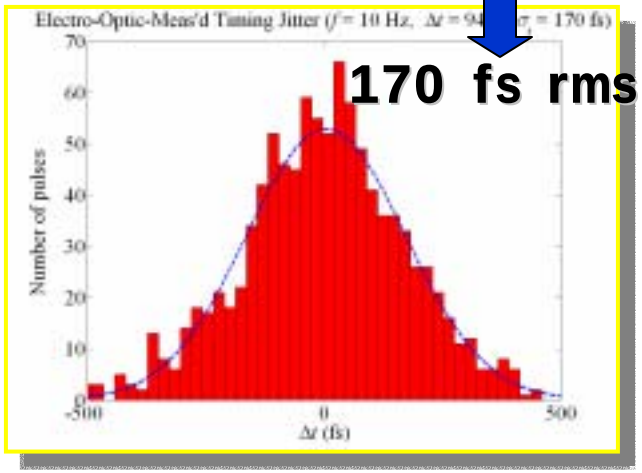
Single-Shot



Timing Jitter (20 Shots)



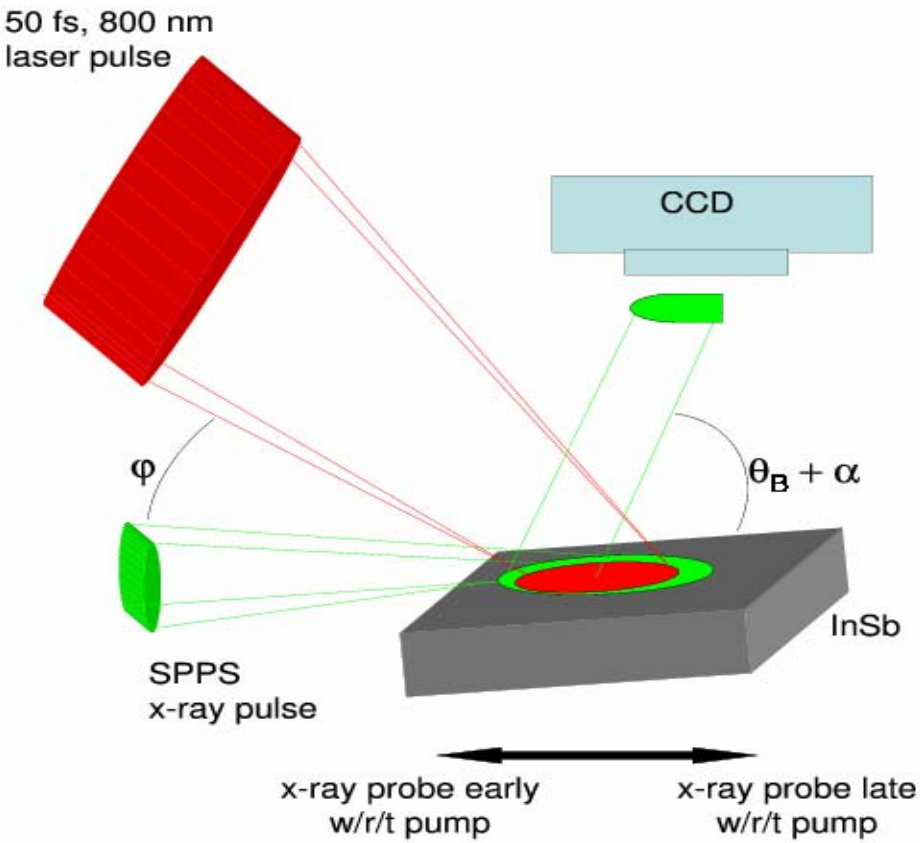
e^- temporal information is encoded on transverse profile of laser beam

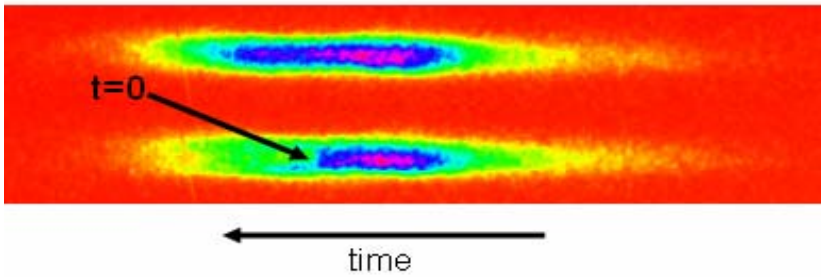


170 fs rms

Adrian Cavalieri et al., *U. Mich.*

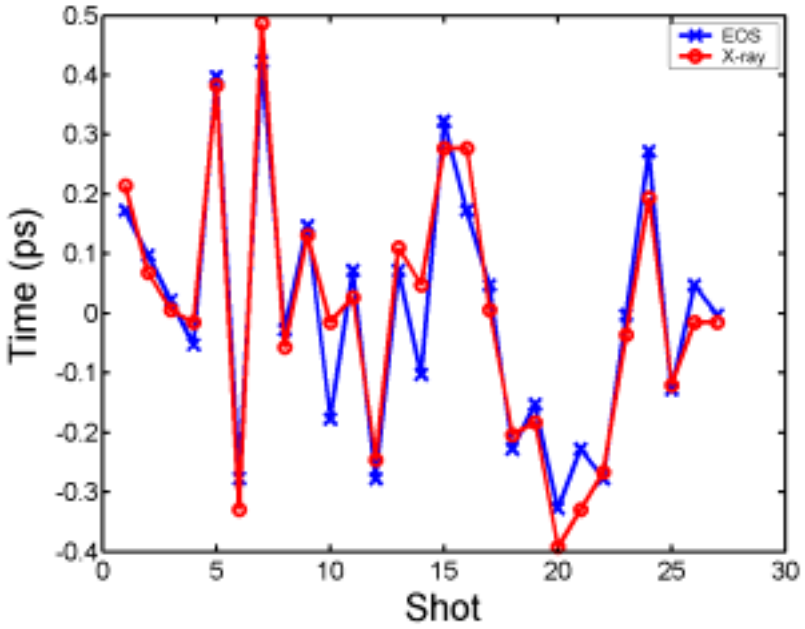
Structural phase transitions with sub-picosecond resolution

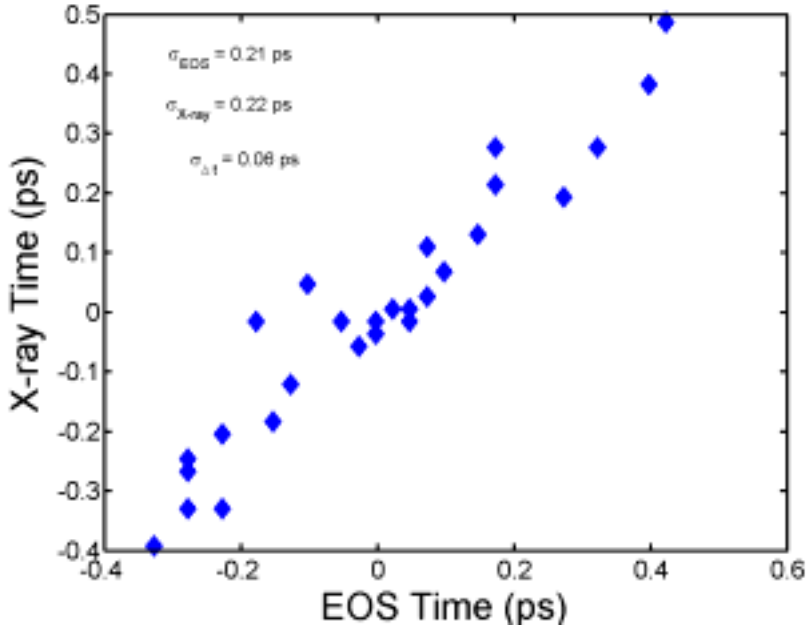




- For j = 24 deg and x-rays grazing: ~18 fs/pixel
- Measures complete time history around t=0 in single shot

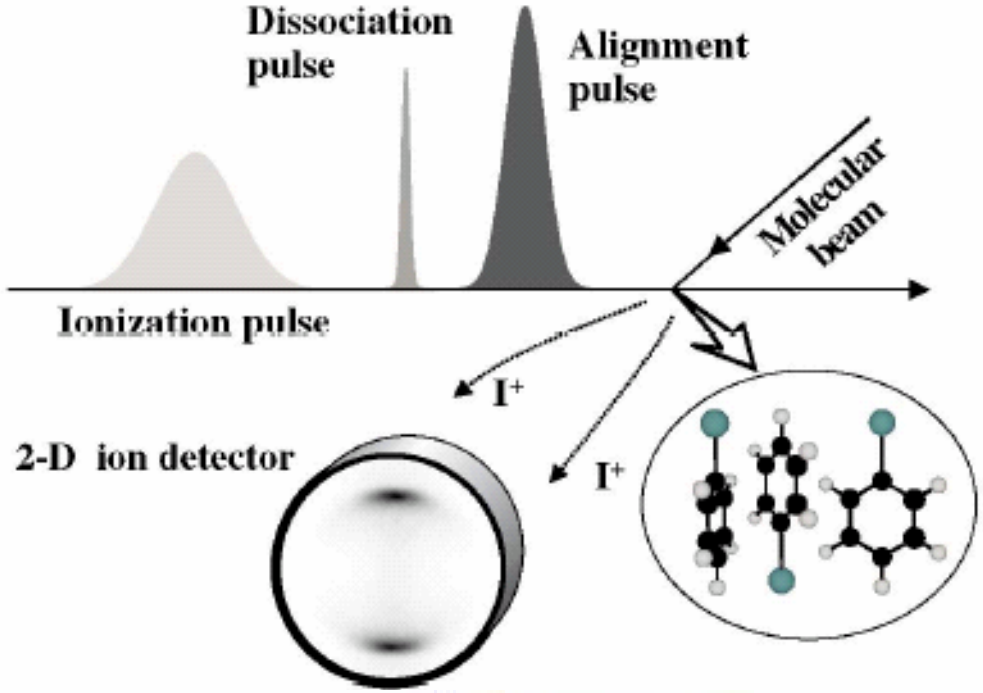
Melting/EO Comparison





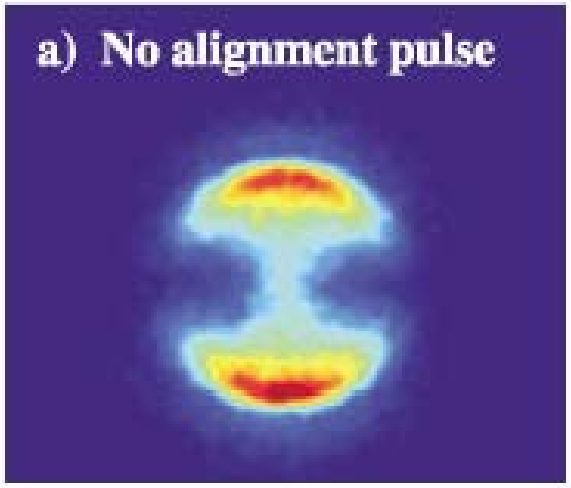
•Electro-optic sampling technique (sensitive to electron beam timing) agrees with location of edge in melting data to < 100 fs (60 fs rms)

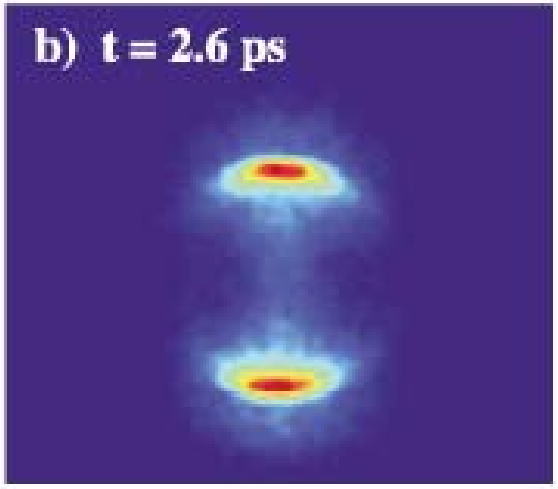
Many experiment require picosecond x-rays:



Transient alignment of molecules

(Here, C_6H_5I viewed by photo-dissociation)





Peronne et al.
Phys. Rev. Lett. **91**, 043003 (2003)

APS and ultrafast x-ray science

- SPPS is showing the promise and potential of ultrafast x-ray science
- 3d generation sources, with their high brightness and good access, have a big contribution to make to this area
- APS should study the feasibility of ultrafast pulse compression